Columbia University

Lamont-Doherty Geological Observatory

Palisades, N. Y. 10964

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13. ABSTRACT

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The spatial coherence of 1-5 min acoustic waves from two nuclear explosions is presented along with atmospheric pressure background noise for the same period band. The spatial coherence of the waves from both explosions is greater than the noise coherence at station separations greater than 6-10 km.

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Abstract

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The spatial coherence of 1-5 min acoustic waves from two nuclear explosions is presented along with atmospheric pressure background noise for the same period band. The spatial coherence of the waves from both explosions is greater than the noise coherence at station separations greater than 6-10 km.

1. Introduction

This report presents the results of studies of atmospheric pressure waves generated by nuclear explosions and recorded on the large-aperture microbarograph array (Fig. 1) and ionospheric Doppler sounder operated by Hudson Laboratories of Columbia University during 1967 and 1968. Section 2 deals with the determination of group velocity dispersion curves of long period atmospheric gravity waves and inferences regarding the height of generation of gravity waves. Section 3 summarizes the results of spatial coherence studies of acoustic waves from two nuclear explosions.

2. Group Velocities of Atmospheric Gravity Waves

2.1 Background

Atmospheric acoustic-gravity waves generated by nuclear explosions have been described by many authors (Tolstoy and Pan, 1970 and references therein). The acoustic and gravity modes that have been detected on ground-level microbarograph arrays propagate with the acoustic group velocity in the lower atmosphere ($\approx$310 m sec^{-1}) and have periods of about 1 to 12 min. The observational characteristics of these waves (periods, velocities, dispersion, etc.) have been quite well-defined and the agreement with theory has been fairly good. Large nuclear explosions have also generated traveling disturbances, observed only in the ionosphere, with longer periods and higher velocities ($\approx$300-800 m sec^{-1}) than have been observed for the ground-level waves. The ionospheric disturbances have been interpreted as internal gravity waves (Obayashi, 1963; Hines, 1967). The characteristics of the ionospheric gravity waves have not been as well determined as those of the ground-level waves due to the greater difficulty of making ionospheric measurements, especially array-type measurements which enhance the signal-to-noise ratio. Observations of ionospheric waves from nuclear explosions have usually been made on data from widely

spaced ionosonde stations. Kanellakos (1967) and Albee and Kanellakos (1968) have studied such properties of the traveling ionospheric disturbances as period amplitude, travel times of leading edge and successive peaks, and the effect of the magnetic field on the response of the ionosphere to the waves. The data from such waves has apparently been unsuitable, however, for attempts to define phase and group velocity dispersion curves for the waves. Only by defining the dispersion characteristics would it be possible to identify the signals as specific modes of gravity waves through comparison with the theoretical dispersion characteristics of gravity waves computed for model atmospheres. However, recent observations for the first time of long period (>12 min), high velocity ($\approx$600m sec^{-1}) waves on a ground level microbarograph array (Tolstoy and Herron, 1970) and of a correlated ionospheric wave (Herron and Montes, 1970) have allowed a description and a tentative identification of an atmospheric gravity wave which may be responsible for some of the traveling ionospheric disturbances reported in the literature.

The long period gravity waves reported by Tolstoy and Herron (1970) were observed in the New York City

area on a large aperture (250 km) 10-station microbarograph array. By utilizing digital beamforming techniques, the signals were detected traveling both the short and long great-circle paths away from the sites of three low altitude nuclear explosions (one in China and two in the South Pacific). The waves were dispersive with periods in the 10-25 min range. Both phase and group velocities were approximately 600m sec^{-1}. These were the first reported observations at ground-level of gravity waves traveling at the higher velocities observed previously only in the ionosphere. Phase velocities of the waves were estimated from the assumed phase velocity that gave the greatest amplitudes of the summed signal in the delay-and-sum beamforming procedure. Group velocity for one of the waves was estimated from the source-receiver distance and the travel-time from the moment of detonation of the nuclear explosion. Additional confidence in the ground-level microbarograph detection of the gravity waves was provided when Herron and Montes (1970), using a vertical incidence Doppler sounder within the microbarograph array, detected evidence of one of the gravity waves at ionospheric altitudes (225km). They noted oscillations in ionospheric reflection height that correlated well with the short and long path microbarograph gravity wave signals from a nuclear

explosion in the South Pacific on Aug. 24, 1968. (The Doppler sounder was not operating at the time of any other nuclear explosions).

In this study, average group velocities for all the observed waves have been computed by using travel times from the source locations to the receivers. However, the travel times that should be used to compute group velocities are not the times from the moments of detonation of the nuclear explosions. Rather, it appears that subtractions to the travel times must be made for the time required for the disturbances from the low altitude explosions to rise to ionospheric heights and to set the atmosphere into oscillation at the relatively long periods of 10 to 25 min. Introducing a correction for such a source effect into the calculations of group velocities raises them by 15-20 percent over the uncorrected values.

Recent papers by Harkrider and Wells (1968) and Tolstoy and Pan (1970) have discussed the propagation characteristics of a high velocity wave which travels in the upper atmosphere and which they have referred to as an atmospheric surface wave. Tolstoy and Pan (1970) point out the distinction between internal and surface gravity modes. They state that waves with group veloc-

ities less than about 500 m sec^{-1} correspond to internal modes and that velocities greater than 500 m sec^{-1} correspond to the surface mode. Based mainly on the observed velocities, Tolstoy and Herron (1970) tentatively identified the high velocity waves detected on the microbarograph array as belonging to the surface mode. The modal identification was tentative because the preliminary analysis of group velocities was incomplete and somewhat crude. The more precise and complete analysis of the gravity wave data described in this paper raises the group velocities putting them more definitely in the range of surface mode velocities as calculated by Harkrider and Wells (1968) and Tolstoy and Pan (1970). In addition, this paper points out a second observation in the ionosphere of the Aug. 24, 1968 gravity wave on an ionospheric phase-path sounder system located near Washington, D. C. This observation provides additional information about the characteristics of the wave.

2.2 Group velocity dispersion curves

The detection of the gravity waves on the ground-level microbarograph array (Tolstoy and Herron, 1970) was somewhat marginal in that the signal to noise

ratio on any individual microbarograph was generally less than unity. A delay-and-sum array processing technique was just able to enhance the signal-to-noise ratio to a point where the actual shape of the signal waveform could be studied. Consequently the group velocity dispersion curves from the microbarograph data were determined from the summed signals from an array of instruments. However, as reported by Herron and Montes (1970), and as further shown in this paper, the signal-to-noise ratio of the gravity waves when detected by ionospheric instruments is considerably higher than unity. Thus the group velocities from the ionospheric observations are based on analysis of signals from single instruments.

Fig. 2 shows the waveforms of two of the gravity waves detected by the microbarograph array. The waveforms shown are the sum of the traces from the stations of the array after time shifting the traces relative to one another by an amount determined by the assumed phase velocity (600m sec^{-1}) and the known azimuths of the array from the nuclear test sites. The waveforms of Fig. 2 have been abstracted from beamforming displays of several hours of data beamformed over a full 360° azimuth.

The group velocity dispersion was measured by the method of plotting arrival times of peaks and troughs of the wave-train versus the numbered peaks and troughs. The slope of any point on such a plot gives the period of the wavetrain corresponding to that arrival time. The group velocity corresponding to that period and arrival time is obtained from the source-receiver distance and the travel time.

Fig. 3 shows group velocity curves of gravity waves from several nuclear explosions. Some of the curves were obtained from the short great-circle path arrivals. Other curves were obtained from the antipodal long path arrivals. Fig. 3 includes results from both microbarographic and ionospheric observations. The latter will be discussed in the next section. The dates of the nuclear tests and the instruments used for observation are given in Fig. 3.

The waveforms in Fig. 2 show the sense of dispersion observed for the gravity waves. The long period components of the waves travel fastest. This same type of dispersion was found for both the short and long great-circle path arrivals from three different nuclear explosions.

An examination of Fig. 3 reveals that in the four cases where curves were obtained for both a short and long path arrival, the velocity is higher for the antipodal-path arrival. A possible explanation for the different velocities over the two paths is that the travel times used were too high, that is, that these very long wavelength signals (400-800km) were not initiated at the instant of detonation. Rather than assume that the gravity waves were generated at low altitudes, we can hypothesize that it required many minutes or tens of minutes for the disturbances from the low altitude explosions to rise to ionospheric heights and to there disturb the surfaces of equal density over a large enough area to set the atmosphere into oscillation at the relatively long periods of the gravity waves (10-25min). In fact, Greene and Whitaker (1968), through hydrodynamic calculations of the arrival times of disturbances at ionospheric heights, from low altitude explosions, have predicted the generation of gravity waves at the 120km level at about 600sec after detonation. If the gravity waves were generated at ionospheric heights, then the group velocities in Fig. 3 were computed using travel

times that were too large since the travel times were measured from the moment of detonation. For the nuclear test sites involved, the long great-circle path was approximately three times the length of the short path. Using travel times that are too large has therefore the greatest depressing effect on the short path velocities. If the travel times are shortened, that is, corrected for the generation time of the gravity waves, in order to bring the short and long path velocities into coincidence, the group velocity curves are raised 15 to 20 percent into the positions shown in Fig. 4. These travel time subtractions are necessary for signals from both nuclear test sites involved here: the South Pacific site for which the short path signal azimuth was S 50°W and the China test site for which the short path azimuth was due north. Table 1 lists the travel time corrections for the three nuclear explosions for which gravity waves were detected. All of the corrections are at least as large as the generation time predicted by Greene and Whitaker (1968) for gravity waves from low altitude explosions.

Table 1. Travel time corrections

Date	Instrument	Travel time Correction (sec)
6-17-67	MBAR	3380
7-15-68	MBAR	2000
8-24-68	MBAR	800
8-24-68	Doppler sounder	1400

The explanation offered above is that the difference in group velocities over the short and long paths is a source effect, that is, that the waves actually traveled with the same average velocities over the two paths, but that the computed velocities differed due to an error in the assumed origin time at which the waves began traveling at their full velocity. An alternative explanation is that the different velocities resulted from a propagation path effect, that is, that the waves did in fact travel slower over the short path due to the effects of winds in the upper atmosphere. Winds of 10 to 20 percent of the gravity wave speed have been observed in the upper atmosphere (Kochanski, 1964). If the gravity wave faced a head wind over much of its short path and/or a tail wind over much of its long path, then the velocities could possibly differ by the values observed. However, while it is conceivable that a global pattern of high altitude winds affected the gravity wave velocities as described, it seems unlikely to be entirely responsible for the velocity difference effect for the following reason. The limited evidence available concerning the global pattern of upper atmospheric winds indicates that the direction of the winds changes greatly or even reverses over distances of the order of thousands

of kilometers (Maeda, 1966; Kohl and King, 1967). The same velocity-difference effects between the short and long paths were observed for waves from two widely separated nuclear test sites for which the paths to the New York recording site were 50° different in azimuth. Furthermore, in each case, the waves traveled so far (≈10,000 km for the short path and ≈30,000 km for the long path) that one would expect some cancelling out of wind effects. A similar cancelling of wind effects occurs for the ≈310 m sec^{-1} acoustic-gravity waves commonly recorded at world-wide microbarograph stations following nuclear explosions. Yamamoto (1968) has made a study of the distribution over a large portion of the earth of the propagation velocity of the acoustic-gravity wave from a large Soviet nuclear explosion. Working from isochrone maps of travel time of Wexler and Hass (1962), Yamamoto calculated transit velocities between gridpoints for every 10° of latitude and longitude. The velocities with which the acoustic-gravity wave traveled over various parts of the earth ranged from 250 to 350 m sec^{-1}. In certain geographic areas, the differences of transit velocities between the short and long great-circle waves were as high as 50 to 100 m sec^{-1}. These differences were attributed to

winds of 25 to 50 m sec^{-1} along the propagation direction. Despite the wide geographic variations in speed revealed by Yamamoto's study, the average group velocities of these waves over their entire propagation paths (from the nuclear test sites to the recording stations) seldom vary below 300 or over 320 m sec^{-1}. Fig. 5 shows the average propagation path group velocities of acoustic-gravity waves from 12 different nuclear explosions to 10 different recording stations in different parts of the world. The group velocities were calculated using the origin times and epicentral distances given with the catalog of nuclear explosion waves of Donn and Shaw (1967). In each case the travel times were measured to the arrival time of energy of 7 min period. As seen in Fig. 5, the average group velocities over distances of thousands of kilometers average out much of the wind effect described by Yamamoto. Over propagation paths of 10,000 km or more, the velocity variations are less than 3 or 4 percent of the wave speed.

If there is a cancelling of wind effects for the waves discussed above (of wavelength 100-140 km), it seems likely that the even longer wavelength (400-800 km) gravity waves would also experience a cancelling of wind effects over distances of 1/4 the earth's circumference or more. Wind effects can either raise or lower a short

path velocity relative to a long great-circle path velocity depending on the directions of the winds. The fact that each of the 3 long period gravity waves had a higher long path velocity is support for its being a source effect.

Thus, in view of the expected cancelling of wind effects and the repeated pattern of higher long path velocities, it is suggested that the observed velocity difference over the two paths is for the most part a source effect due to the "rise time" of the nuclear disturbance to the ionosphere, and the time required to disturb the surfaces of equal density at ionospheric levels over a large enough area to launch a 400-800 km wave.

2.3 The ionospheric observations

As reported by Herron and Montes (1970), a vertical incidence ionospheric Doppler sounder was operating in the New York City area during the South Pacific nuclear explosion of Aug. 24, 1968. The Doppler sounder measured the rate of change of vertical motion of electrons in the ionosphere. A cw signal (4.8 MHz) was transmitted from near the center of the microbarograph array and received at a station 36 km distant after having been reflected from the lower F region ($\sim$225 km) of the iono-

sphere at nearly vertical incidence. The gravity waves discussed in this paper propagated with wavelengths of several hundred kilometers and thus involved motion of a large part of the atmosphere including the ionospheric regions. The gravity wave generated by the Aug. 24, 1968 explosion produced frequency shifts in the Doppler sounder signal. Fig. 6 shows the Aug. 24 Doppler record before and after application of an 8-21 min bandpass filter. The group of oscillations in Fig. 6 is the signal that correlated in time with the _short_ great-circle path gravity wave signal detected on the microbarograph array (Herron and Montes, 1970). A smaller amplitude oscillation at a later time (not shown in Fig. 6) correlated with the _long_ great-circle path array signal (Herron and Montes, 1970).

The microbarograph gravity wave signals showed measurable group velocity dispersion. In contrast, an examination of the ionospheric oscillation of Fig. 6 reveals no obvious dispersion at least over the high amplitude parts of the wavetrains which are nearly sinusoidal. This may be because the dispersion is very slight for this particular signal and is obscured by background noise in the lower amplitude parts of the wavetrain. Even the corresponding microbarograph signal

for Aug. 24 (Fig. 2) doesn't show a great deal of dispersion compared to the June 16 signal. The best we can do for the oscillation of Fig. 6 is to measure the travel time to the time of maximum amplitude of the group and assign the resulting group velocity to the period of the group. Taking 2305 GMT as the center and maximum amplitude of the Doppler signal of Fig. 6, we obtain a group velocity of 590 m sec^{-1} and a period of 12.5 min. A similar treatment of the long path Doppler signal, which was also nearly sinusoidal, gave a velocity of 623 m sec^{-1}. As far as it is valid to compute average group velocities for sinusoidal groups, as done above, we find the short path Doppler signal group velocity to be less than the long path group velocity, as was the case for the microbarograph signals. If we now go so far as to shorten the travel times for the short and long path Doppler signals, in order to bring the short and long path velocities into coincidence (at 631 m sec^{-1}), we find that the travel time correction is a subtraction of 1400 sec. This does not agree very closely with the travel time correction for the corresponding microbarograph signal of Aug. 24 (800 sec), but is at least of the same order. The difference is probably due to the inaccuracy of measuring the group velocity of an almost single frequency group of oscillations. We have at least shown that the Doppler sounder signals show

a group velocity difference for the short and long paths as do the microbarograph signals and that the Doppler signal travel times require a subtraction to bring the velocities into coincidence.

In addition to the Doppler sounder, which was in the New York City area, an ionospheric phase-path sounder system was operated near Washington, D. C. The phase sounder was a coherent pulse radar system operated at about 6.5 MHz. It measured the distance to electron density gradients for oblique as well as for vertical ionospheric echoes. The record of Fig. 7 provided by H. F. Busch (private communication) was obtained during the Aug. 24 nuclear test. It shows several interesting features. A "range-closing" oblique echo is seen that results from a horizontally traveling F region disturbance which passed overhead at 2230 GMT. Coincidental with the overhead passage of the disturbance, a sudden decrease in F. region electron density occurred as seen in the bahavior of the ordinary mode reflection at 2230 GMT, at about 274 km true height. The extraordinary ray reflection at a lower elevation (about 239 km true height) shows a series of oscillations beginning at about 2230 GMT. Taking the travel time to the center of this group of oscillations (2255 GMT) gives an average group velocity of 590 m sec^{-1} for the group whose average

period is 16 min. The long antipodal-path signal was not observed on the phase sounder, so that no estimate of a travel time correction can be made. The periods of the Doppler and phase sounder signals (12.5 and 16 min) are within the range of periods of the corresponding dispersed microbaragraph signal (11 to 18 min) for Aug. 24, 1968. The phase sounder was about 307 km closer to the nuclear test site than was the Doppler sounder. The phase sounder oscillation occurs appropriately early compared to the time of the Doppler oscillation so that average group velocity to each instrument site was 590 m sec^{-1}. The phase sounder data provides important confirmation that the ionospheric oscillation seen in the Doppler data is a traveling wave corresponding to the wave observed at ground-level on the microbarograph array. Without the observation of the ionospheric wave delayed the appropriate amount between the two ionosounders it could be argued that the Doppler sounder oscillation was not a traveling wave and was unrelated to the microbarograph signal which was, of course, delayed across the array.

Information regarding the vertical displacements

of electrons and neutral particles at ionospheric heights due to the gravity wave can be extracted from the data. Nelson (1968) has discussed the response of the ionization at F region heights to the passage of a wave supported by the neutral particles of the atmosphere. Since the ion gyrofrequency is much greater than the ion-neutral collision frequency in the F region, the motion of the ions is along the magnetic field lines with coulomb forces causing corresponding motion of the electrons. Thus the electrons take on the component of neutral wave motion along the magnetic lines of force and the vertical component of this motion produces Doppler shifts in the frequency of reflected rays. In the New York area where the inclination of the geomagnetic field lines is about 72°, the vertical displacement of the neutral particles will be just slightly greater than that of the electrons. In addition, the vertical displacement of electrons can be related to the observed Doppler shift of a radio wave vertically incident upon the ionosphere (Davies and Baker, 1966). From the Doppler shift of 1 Hz at a 12.5 min period (Fig. 6), Herron and Montes (1970) estimated the vertical displacement of electrons

associated with the passage of the Aug. 24, 1968 gravity wave to be about 5 km peak to trough at a true height of about 225 km. The displacement of the electrons due to the gravity wave can also be estimated from the phase sounder record. A true height analysis for the region of Washington, D. C. indicates that the extraordinary ray height oscillations of the gravity wave signal in Fig. 7 are about 6 to 8 km at a height of approximately 239 km. A vertical displacement of electrons of 5 to 8 km implies a vertical displacement of the neutral particles of about 6 to 9 km since the inclination of the geomagnetic field lines is about 72° in the New York area. Tolstoy and Pan (1970) have argued that neutral particle displacements of this order are not inconsistent with the ground-level pressure amplitude of about 40 μb observed for the Aug. 24 gravity wave.

The detectability of the gravity waves at ground-level can be compared to the detectability in the ionosphere. The results of Tolstoy and Herron (1970) showed the signal-to-noise ratio on a <u>single</u> microbarograph (not on the summed array) to be usually less than unity, perhaps 1/2 or 1/3. In contrast Herron and Montes (1970) estimated the signal-to-noise ratio of the gravity wave on the Doppler sounder to be about 3 to 1. Fig. 7 shows

the signal-to-noise ratio on the phase sounder to be well above unity. It appears then that in some instances the signal-to-noise ratio in the long-period gravity wave range (10-25 min) may be a half an order of magnitude or more higher in the F region of the ionosphere than at ground-level where a rather high level of jet-stream generated background noise exists in the mesoscale period range (Herron et al., 1969). The above results suggest that further study of long-period gravity waves should probably be made by ionospheric measurements.

2.4 Discussion of results

If we accept the suggestion that the group velocity differences between the short and long paths are mostly a source effect rather than a propagation path effect due to wind, then it is valid to compute the travel time subtraction necessary to make the velocities for the two paths equal. The travel time corrections can be explained as the time required for a disturbance to rise from a low altitude explosion to ionospheric levels and to there generate gravity waves as predicted by the calculations of Greene and Whitaker (1968). Table 1 shows that the travel time corrections range upward from 800 sec. Since little is known of the generation mechanism of long period gravity waves, these results

are significant in providing experimental evidence that the gravity waves are generated at ionospheric levels at about 13 minutes or more after a low altitude explosion.

Figs. 3 and 4 show the theoretical group velocity curves computed by Tolstoy and Pan (1970) for a two-layer compressible model of the atmosphere. The curves are for the fundamental waveguide mode, m=0 (the surface mode), and the first internal mode, m=1. Fig. 4 shows, in addition, the theoretical group velocity curves of Harkrider and Wells (1968) for the long period branch of the fundamental acoustic mode, which they identify as an atmospheric surface wave. The curves are computed for free surface models terminated at altitudes of 220, 310 and 490 km. As seen in Fig. 3, the uncorrected group velocities scatter between the surface and first internal modes of Tolstoy and Pan, making modal identification of the observed waves uncertain. If the travel time corrections are valid corrections for a source effect, then we would expect the corrected group velocity curves of Fig. 4 to fit more closely to one of the theoretical curves. The corrected curves of Fig. 4 do cluster about the surface mode curve of Tolstoy and Pan and, also, fall in the range of surface wave velocities given by Harkrider and Wells, thus supporting the

tentative identification of these signals by Tolstoy and Herron (1970) as surface gravity waves. The better agreement of the observed group velocity curves among themselves and with the theoretical surface mode curves when the corrections are applied is added evidence that the travel time subtractions are valid corrections. Calculations of Harkrider and Wells (1968) have indicated the inefficiency of a low altitude explosion in generating an atmospheric surface wave. Their studies show that the most efficient source region is above 130 km, supporting the suggestion that the travel time subtractions represent the time for a low altitude disturbance to rise to the ionosphere and generate the waves at high altitudes. While it is apparent that the limited data (from only 3 nuclear explosions) is inadequate to rule out all effect of high altitude winds on the travel times, it should be restated that the waves traveled such large distances that we would expect considerable cancelling of wind effects.

2.5 Conclusions

Observations of ionospheric waves from nuclear explosions and natural sources have been widely reported. In many cases the experimental control has not been great enough to accurately define such characteristics

of the wave as period, amplitude, velocity, attenuation, with range, frequency dispersion, etc. The analyses of Tolstoy and Herron (1970), Herron and Montes (1970), and of this present paper, of waves from a known source, traveling both ways around the earth, detected at ground-level and at two points in the ionosphere have allowed a fairly complete description of one type of atmospheric gravity wave.

1) The observations show that large nuclear explosions can generate atmospheric gravity waves of periods 10-25 min. with group velocities in the 550-700 m sec^{-1} range.

2) Unlike the slower (310 m sec^{-1}), shorter period (1-5 min) acoustic waves also generated by nuclear explosions, modal identification of the long period gravity waves requires a correction to the travel times when computing average group velocities from a low altitude explosion. A subtraction of about 13 or more minutes must be made. The correction is attributed to the time for the disturbance to rise to ionospheric levels and to there disturb the surfaces of equal density over a large enough area to generate waves of 400-800 km wavelengths.

3) The corrected group velocities agree with the theoretical group velocities given by Harkrider and Wells

(1968) and Tolstoy and Pan (1970) for the wave which they refer to as an atmospheric surface wave.

4) The measured vertical displacement of electrons for the Aug. 24, 1968 gravity wave was 5-8 km in the lower F region of the ionosphere and this corresponded to observed ground-level pressure perturbations of about 40 μb. The vertical displacement of neutral particles was inferred to be about 6-9 km.

5) The ionospheric observations showed that for the Aug. 24 gravity wave the signal-to-noise ratio was half an order of magnitude or more higher in the F-region than at ground-level.

3. Spatial Coherence of Acoustic Waves

3.1 Observations

Two nuclear explosions in the South Pacific in 1968 (Aug. 24 and Sept. 9) produced acoustic waves where the signal to noise ratio was sufficiently high to allow a reliable determination of the spatial coherence of the signal. For the other explosions in 1967 and 1968, the signal to noise ratios were so low that the measured coherencies would not approach the true coherencies of the signals due to degradation of the coherence by the superimposed background noise.

Fig. 8 shows a power spectrum of one of the microbarograph traces for an 82 min section of record which just encompasses the wavetrain of acoustic signals from the Aug. 24, 1968 explosion. Fig. 9 shows a spectrum of a 60 min acoustic wavetrain from the Sept. 9, 1968 explosion. Humps in these spectrums between about 1 and 6 min period are due to the energy in the acoustic modes. The separate modes were found by passing the records through successive ½ octave filters. Modes in the 1-2, 2-3, and 3-5 min period bands had the highest signal-to-noise ratios for the August 24 explosion. Modes in the 1-2 and 2-3 min bands had the highest signal-to-noise ratios for the September 9 explosion.

The spatial coherence of the signals in these period bands was studied by computing cross-spectral coherencies of the array records for many pairs of array stations at separations ranging from 7 to 200 km. The digital data were pre-whitened before analysis, a maximum lag of 10% was used in the cross-correlation, and a hanning window was used to smooth the raw spectrums.

A summary of the results is given in Fig. 10 which shows a plot of the signal coherencies versus station separation for the period bands mentioned above for the two nuclear explosions. Also given in Fig. 10 is information on how the spatial coherence of atmospheric pressure background noise decreases with distance. This data is taken from a paper by Herron et al., 1969 and from other analyses performed at Hudson Laboratories. For record lengths of 1 hour the background noise coherence in the period range of acoustic waves lie in the cross-hatched area.

Although there is considerable scatter in the signal coherency data, several observations can be made.

1. There is a clear distinction on the plot between the region of noise coherence and the region of signal coherence. The noise becomes incoherent beyond 4 or 5 km station separation whereas the signals

remain coherent out to separations of tens to hundreds of kilometers

2. For the 2-3 and 3-5 min period bands of the Aug. 24, 1968 explosion, the signal coherencies are plotted for station pairs aligned $\pm 25^{\circ}$ from the direction of signal travel and $\pm 25^{\circ}$ from the normal to the direction of signal travel. The transverse coherencies are higher than the parallel coherencies at large separations, that is, the waves are long-crested.

3.2 Conclusions

To extract signals from noise by array procedures, it is necessary for the signals to have high coherence across the entire array, and for the noise to have low coherence between elements of the array. For acoustic waves in the 1 to 5 min period range, an array with station separations of 6-10 km and an array size of several tens of kilometers would allow the best enhancement of signal-to-noise ratio.

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Figure Legends

Fig. 1. Hudson Laboratories Microbarograph array.

Fig. 2. Gravity waves from two nuclear explosions. The waveforms shown are the summed signals from an array of microbarographs. Group velocity dispersion, with long periods arriving first, can be seen in the waveforms.

Fig. 3. Average group velocities of gravity waves. The solid symbols (D) are for waves which traveled the short great-circle paths. The open symbols (A) are for waves which traveled the long, antipodal great-circle paths. The dates of the nuclear tests and the instruments used for recording are listed. The dashed curves are theoretical dispersion curves of Tolstoy and Pan (1970) for the surface (m=0) and first internal (m=1) gravity modes.

Fig. 4. Corrected group velocities. The source to receiver travel-times were shortened to bring the short and long great-circle path velocities into coincidence. The corrected group velocities fit quite closely to the surface mode theoretical dispersion curve of Tolstoy and Pan (1970) and fall in the range of theoretical surface wave velocities given by Harkrider and Wells (1968) for models with free surfaces at 310 and 490 km.

Fig. 5. Average group velocities (over the entire propagation paths) of acoustic-gravity waves from 12 different nuclear explosions to 10 different recording stations in different parts of the world.

Fig. 6. The gravity wave from the Aug. 24, 1968 nuclear explosion as detected in the New York City area by a vertical-incidence ionospheric Doppler sounder. The unfiltered signal was subjected to an 8-21 min digital bandpass filter. The wave had a 12.5 min period and produced a Doppler shift of 1Hz at an altitude of 225 km true height.

Fig. 7. An ionospheric phase-path sounder record from the Washington D. C. area for Aug. 24, 1968 (provided by H. F. Busch). Note the range-closing oblique echo and the sudden decrease in electron density (ordinary ray echo) at 2230 G. M. T. The extraordinary ray echo shows the gravity wave oscillation beginning at about 2230 GMT. with a period of 16 min and a vertical displacement of about 6 to 8 km at a true height of about 239 km.

Fig. 8. Power spectrum of an 82 min section of record (0304 to 0426 GMT, Aug. 25, 1968) showing spectral peaks that result from acoustic waves. The arrows show period bands in which spatial coherence of the acoustic modes was computed.

Fig. 9. Power spectrum of a 60 min section of record (0345 to 0445 GMT, Sept. 9, 1968) showing energy in the 1-2 and 2-3 min period bands. Spatial coherence was computed for acoustic modes in these bands.

Fig. 10. Coherence versus station separation of acoustic waves from two nuclear explosions and of background noise in the same period range as the acoustic waves.

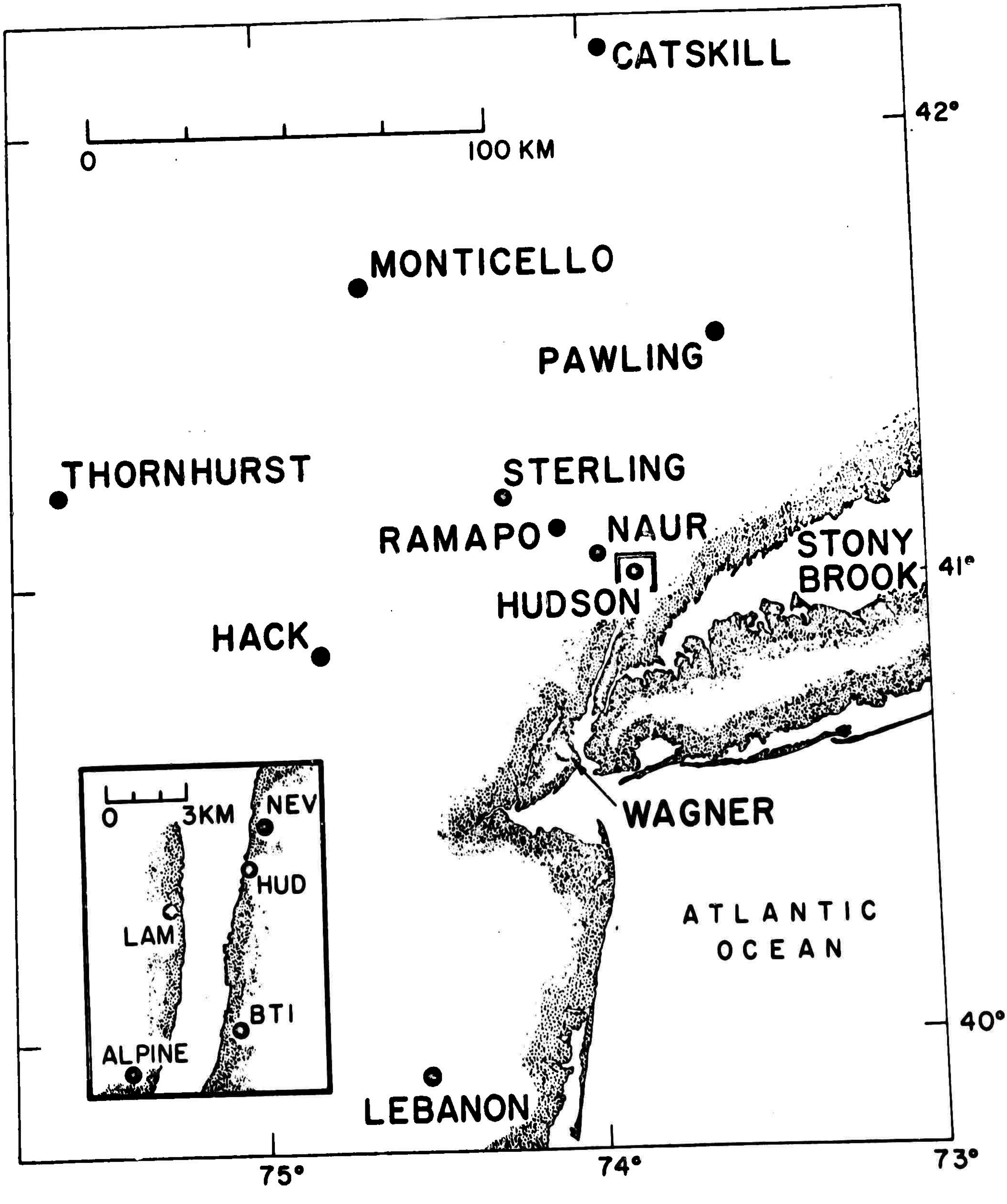

CATSKILL
42°
0
100 KM
MONTICELLO
PAWLING
THORNHURST
STERLING
RAMAPO
NAUR
STONY
BROOK
41°
HUDSON
HACK
WAGNER
0
3KM
NEV
HUD
LAM
BTI
ALPINE
ATLANTIC
OCEAN
40°
LEBANON
75°
74°
73°

Fig. 1

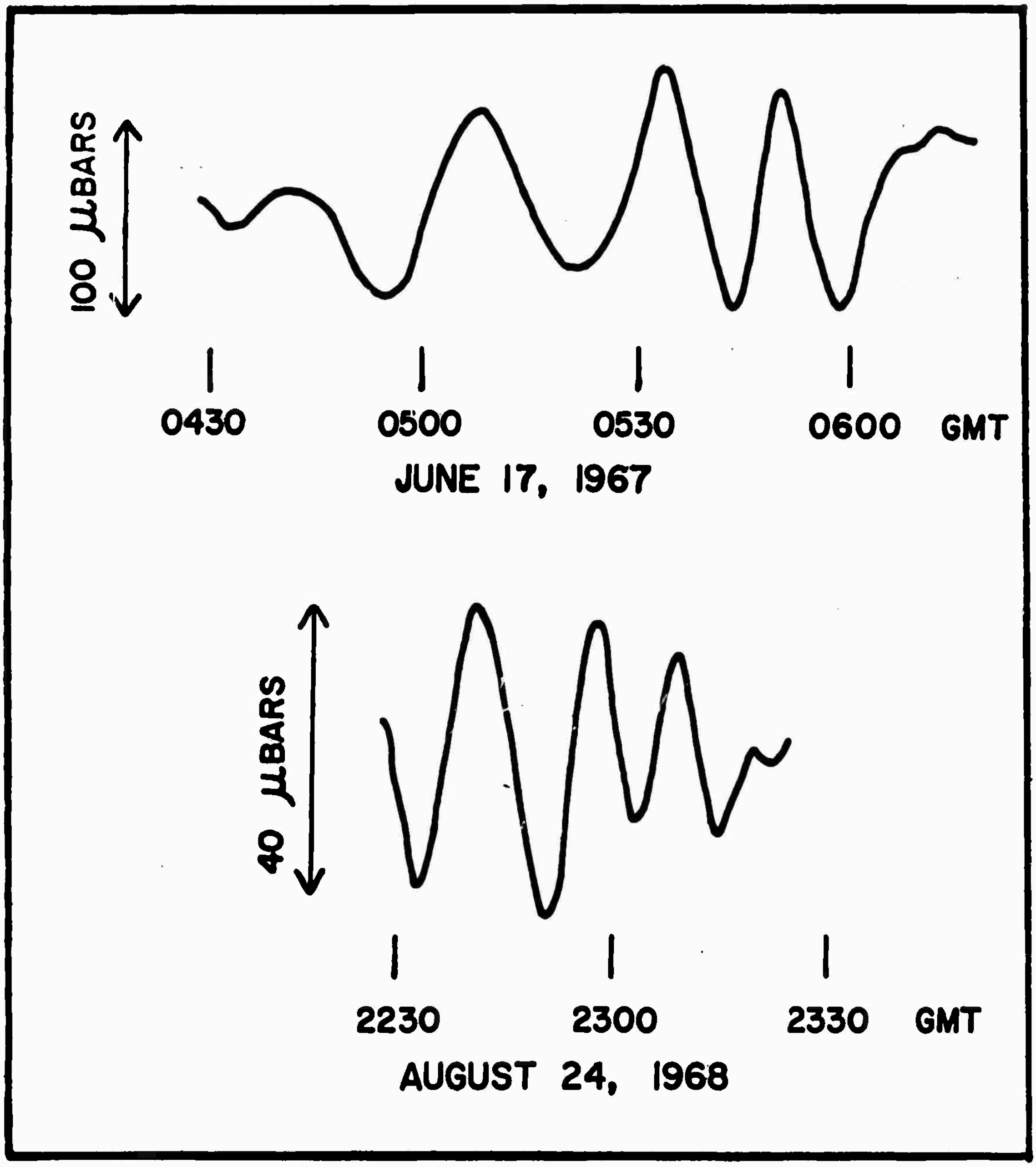
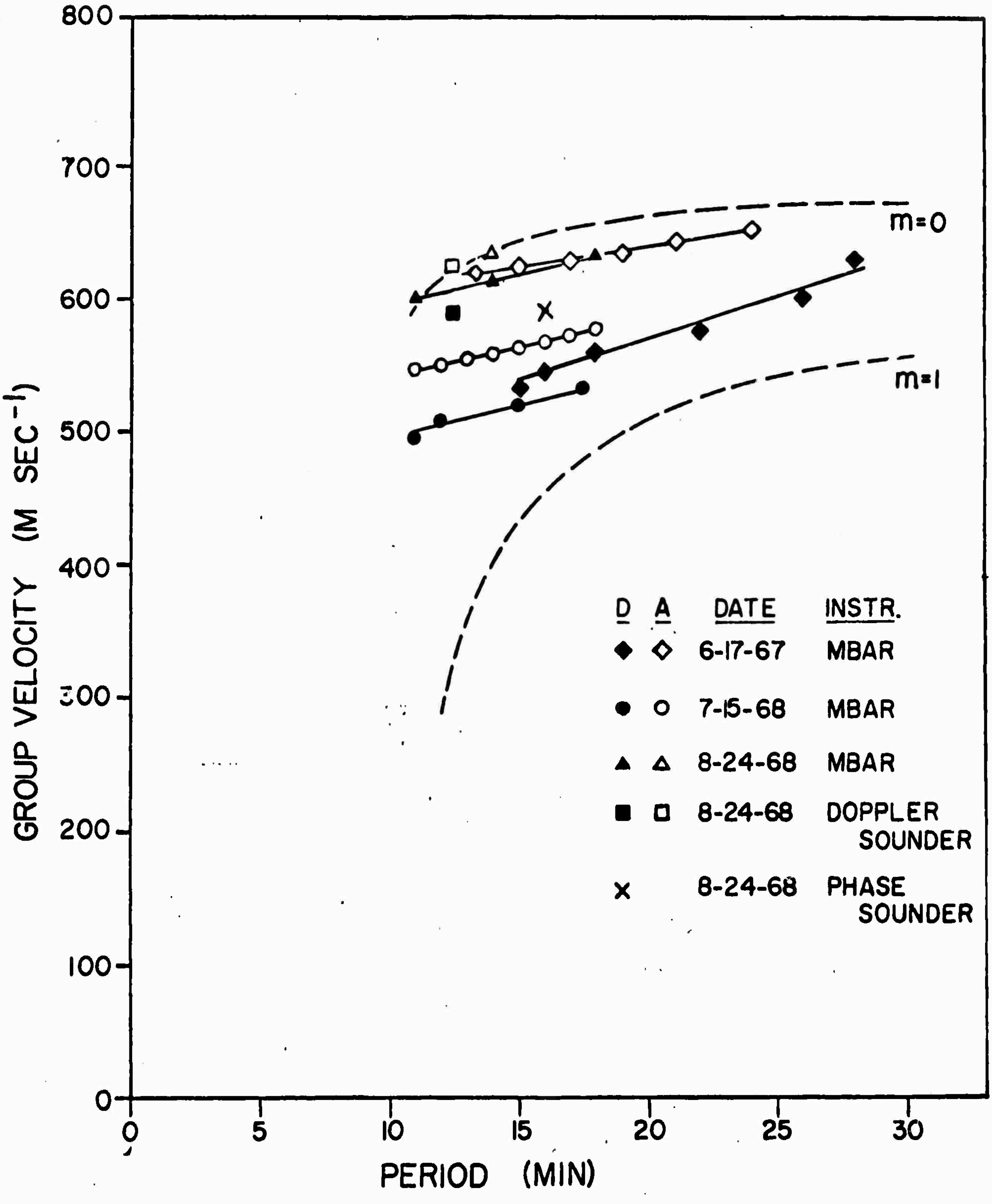
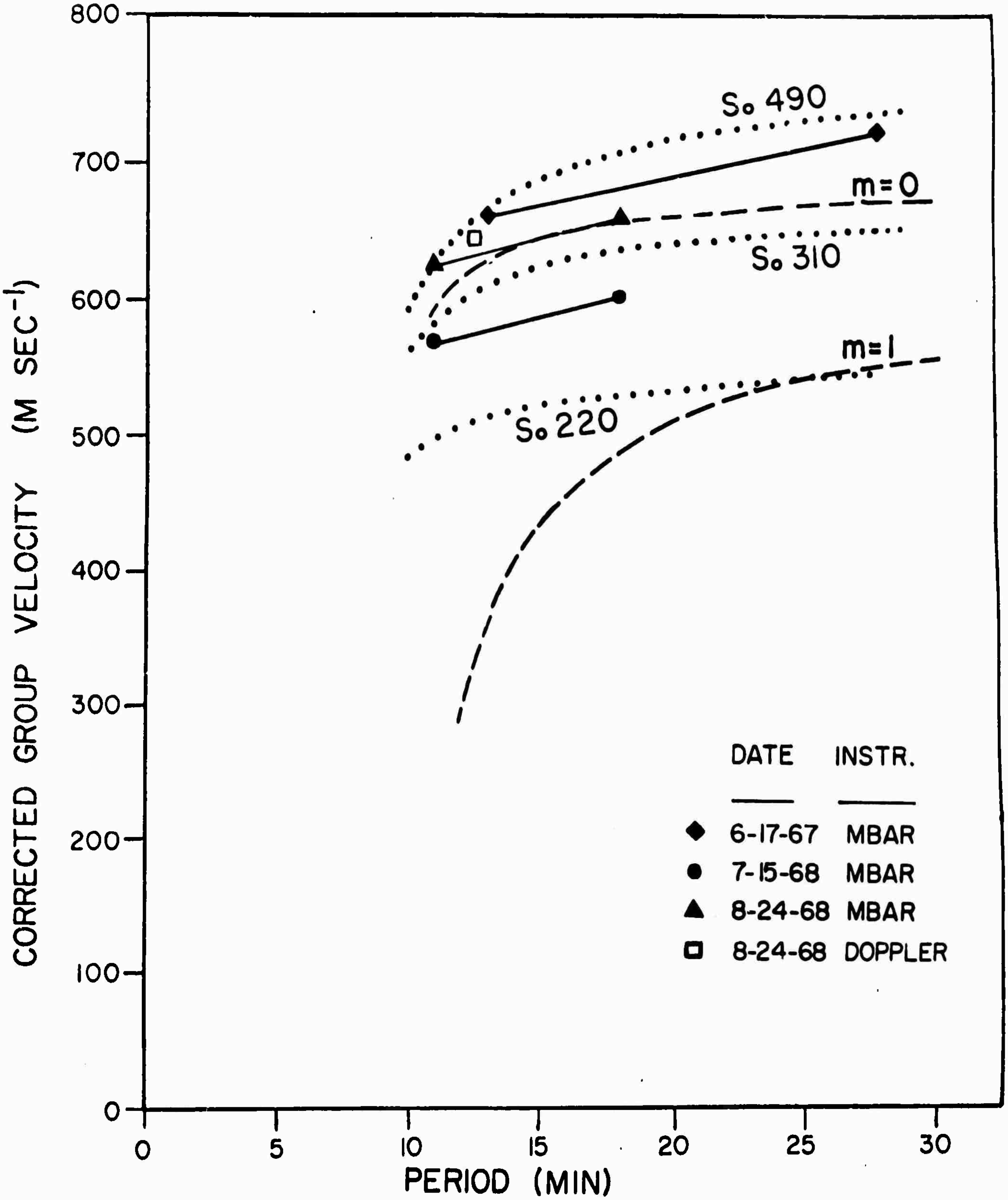

100 μBARS
0430
0500
0530
0600
GMT
JUNE 17, 1967
40 μBARS
2230
2300
2330
GMT
AUGUST 24, 1968

Fig. 2



GROUP VELOCITY (M SEC^{-1})
800
700
600
500
400
300
200
100
0
0
5
10
15
20
25
30
PERIOD (MIN)
m=0
m=1
D A DATE INSTR.
6-17-67 MBAR
7-15-68 MBAR
8-24-68 MBAR
8-24-68 DOPPLER SOUNDER
8-24-68 PHASE SOUNDER

Fig. 3



CORRECTED GROUP VELOCITY (M SEC^{-1})
800
700
600
500
400
300
200
100
0
0
5
10
15
20
25
30
PERIOD (MIN)
S₀ 490
m=0
S₀ 310
m=1
S₀ 220
DATE
INSTR.
6-17-67 MBAR
7-15-68 MBAR
8-24-68 MBAR
8-24-68 DOPPLER

Fig. 4

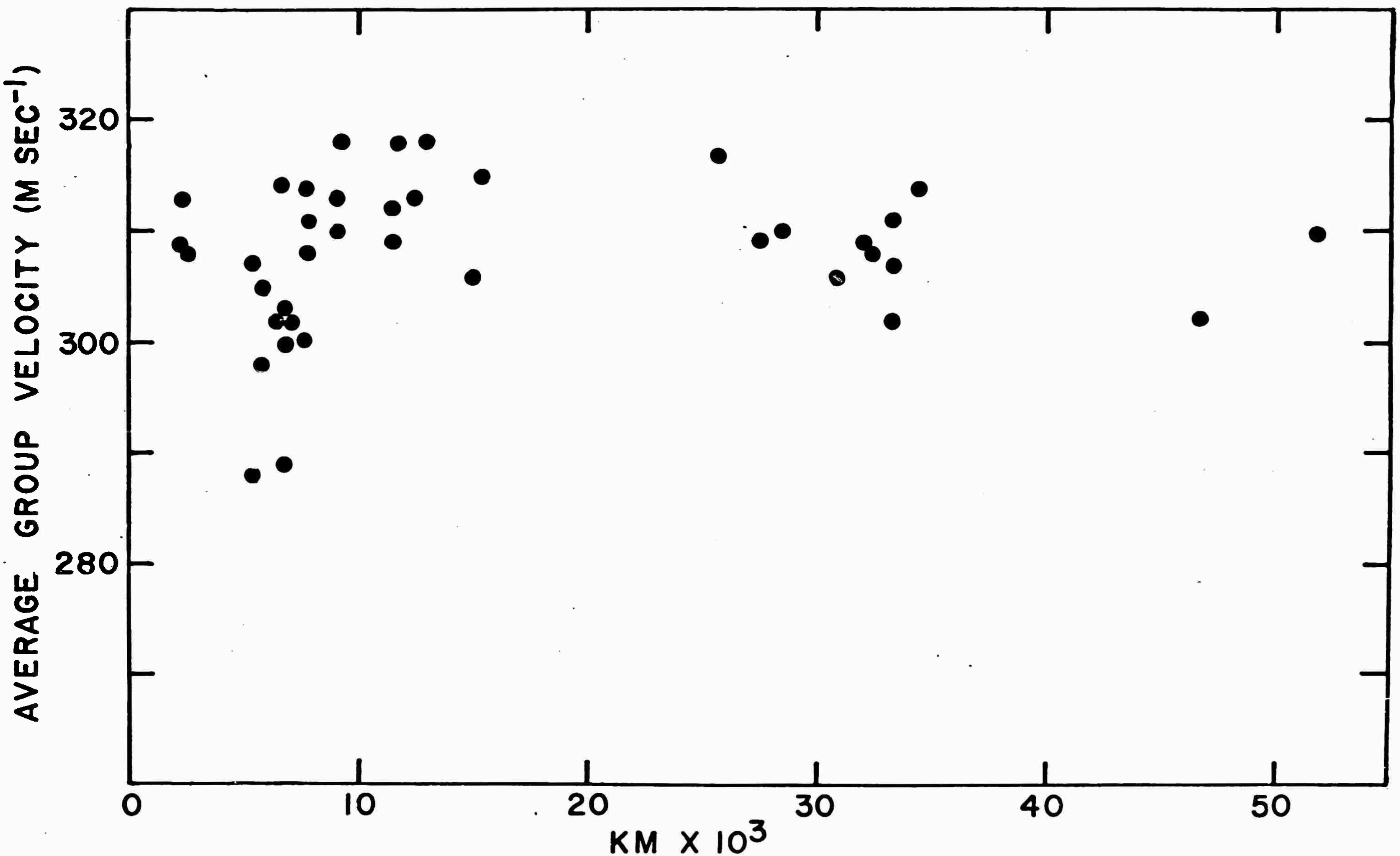

AVERAGE GROUP VELOCITY (M SEC^{-1})
320
300
280
0
10
20
30
40
50
KM X 10^3

Fig. 5

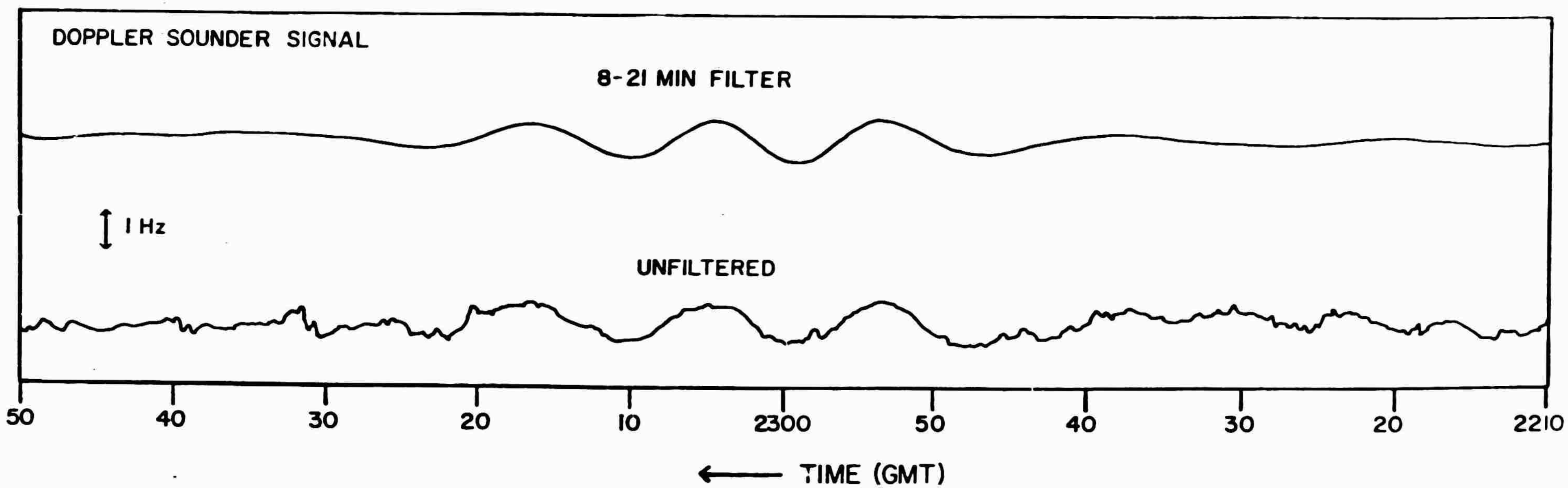

DOPPLER SOUNDER SIGNAL
8-21 MIN FILTER
1 Hz
UNFILTERED
50
40
30
20
10
2300
50
40
30
20
2210
TIME (GMT)

Fig. 6

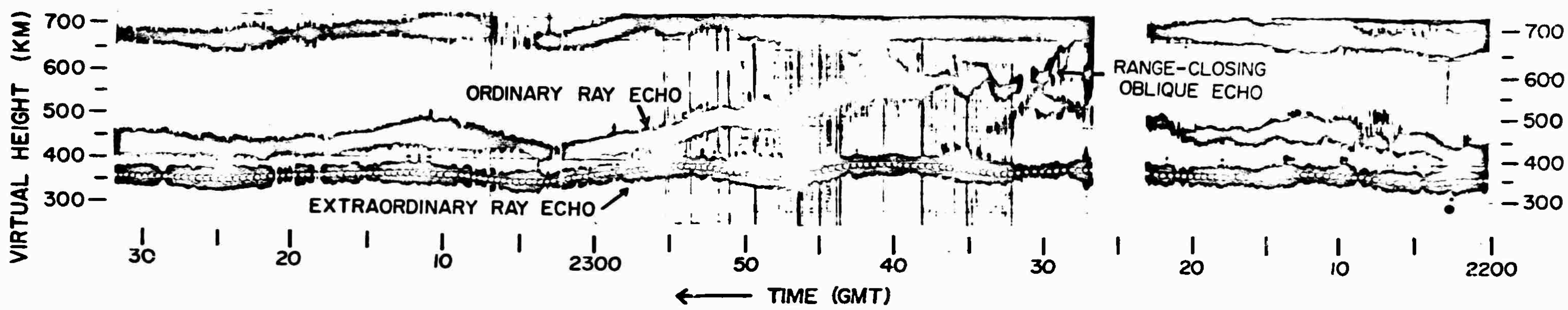

VIRTUAL HEIGHT (KM)
700
600
500
400
300
ORDINARY RAY ECHO
EXTRAORDINARY RAY ECHO
RANGE-CLOSING
OBLIQUE ECHO
30
20
10
2300
50
40
30
20
10
2200
TIME (GMT)

Fig. 7

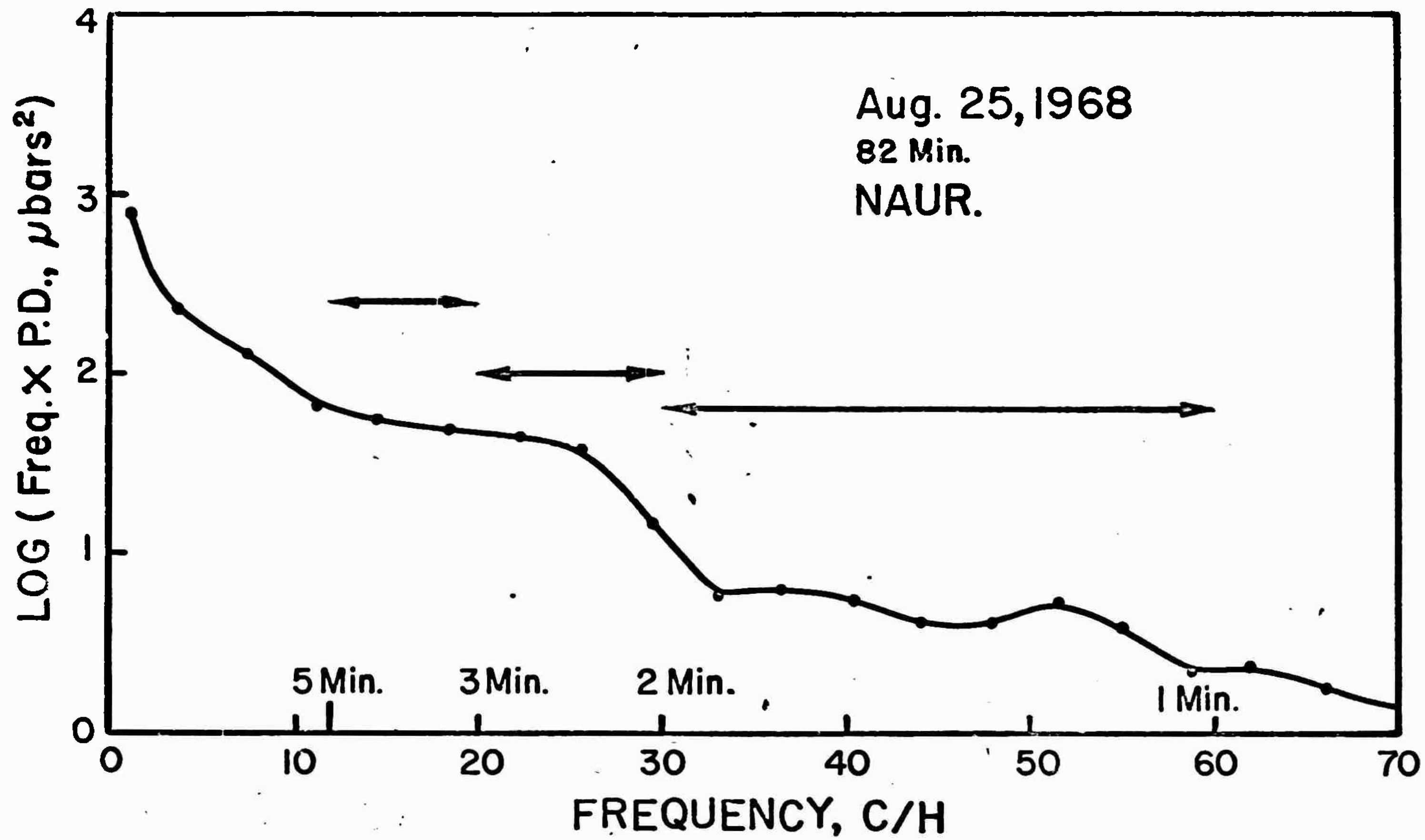

Aug. 25, 1968
82 Min.
NAUR.
LOG (Freq. X P.D., μbars²)
4
3
2
1
0
0
10
20
30
40
50
60
70
5 Min.
3 Min.
2 Min.
1 Min.
FREQUENCY, C/H

Fig. 8

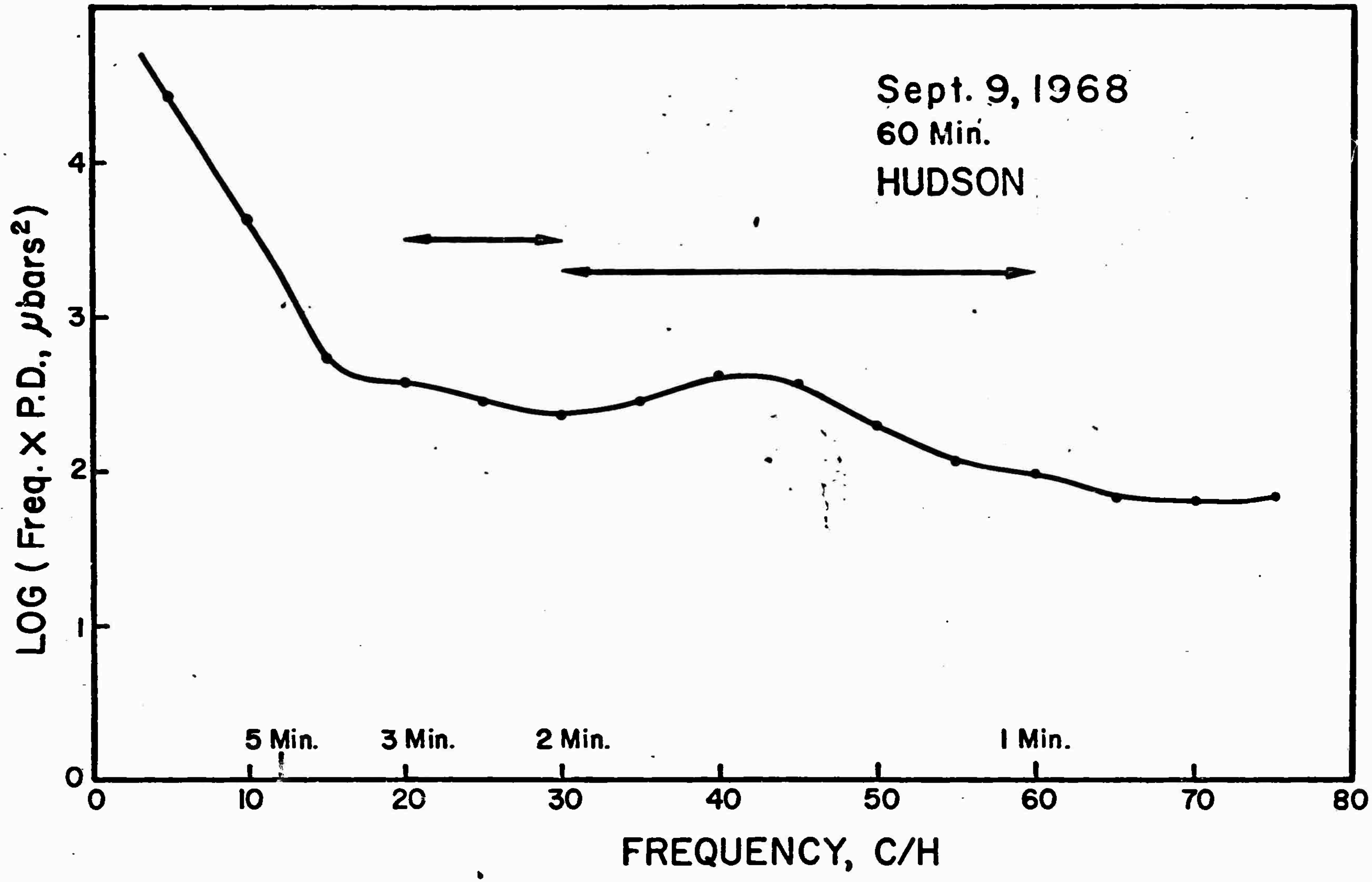

Sept. 9, 1968
60 Min.
HUDSON
LOG (Freq. X P.D., μbars²)
FREQUENCY, C/H
5 Min.
3 Min.
2 Min.
1 Min.
0
1
2
3
4
0
10
20
30
40
50
60
70
80

Fig. 9

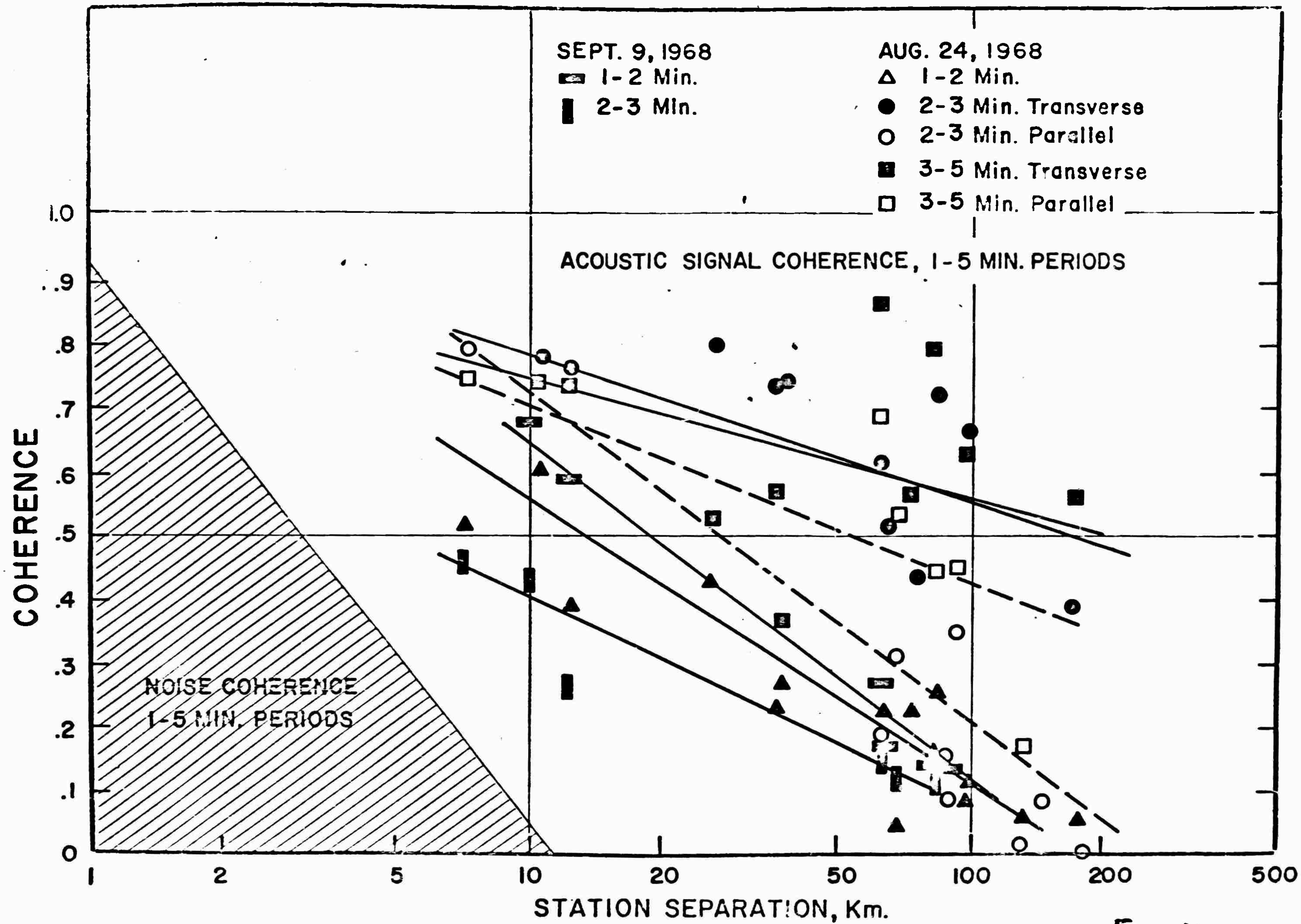

SEPT. 9, 1968
1-2 Min.
2-3 Min.
AUG. 24, 1968
1-2 Min.
2-3 Min. Transverse
2-3 Min. Parallel
3-5 Min. Transverse
3-5 Min. Parallel
ACOUSTIC SIGNAL COHERENCE, 1-5 MIN. PERIODS
NOISE COHERENCE
1-5 MIN. PERIODS
COHERENCE
1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
0
1
2
5
10
20
50
100
200
500
STATION SEPARATION, Km.

Fig. 10